Titan Astroplane: Feasibility Considerations for Unmanned Aerial Vehicle Flight on Saturn's Moon

Ryan Schaefer,
Marshall Brenizer
Adroit Systems, Inc.
(703) 684-2900
(703) 836-7411 fax
rschaefer@alexandria.adroit.com

Bulleted Abstract

- Investigation details a feasibility study for unmanned aerial vehicle flight within a non-terrestrial atmosphere
    - Analyzes a conceptual vehicle from the environmental perspective of Saturn's moon Titan
    - Suggests the viability of operating an unmanned aerial vehicle (UAV) as a planetary probe *in real time*
    - Exploits the burgeoning human/robotic synergy of terrestrial UAVs to keep the astronauts in the safe orbit of the body of interest
- Feasibility study examines design and operational considerations of such a UAV
    - Provides insight into functional requirements, technology roadmaps, and design constraints for UAV operations on Titan
    - Emphasizes such issues as command and control, aerodynamics, structures, and propulsion
    - Utilizes systems engineering tools to relate likely user needs to potential design requirements
- Conceptual mission sets the stage for further studies of what is arguably the most interesting moon in our solar system
    - Explores design and flight requirements in a dense nitrogen and methane rich atmosphere
    - Follows and builds upon the upcoming Cassini mission, which will begin a new insitu study of the Saturn system in 2004 by deploying the Huygens probe into Titan's atmosphere for a limited analysis
    - Stimulates "out-of-the-box" thinking to raise interesting questions and answers about the potential for UAV flight in space

1 Introduction

The launch of Sputnik in 1959 ushered in the era of "unmanned space vehicles." Since that historic launch, the role of unmanned vehicles in the exploration of near and deep space has grown in excitement and dividends, serving roles which were too "dull, dirty, or dangerous" for astronauts. The most mundane tasks have been celebrated when performed by robots; the most abysmal work has been accomplished with no cleanup necessary; and some of the most hazardous challenges have been faced bravely from the safe distance of automation or tele-operation. Indeed, the Voyager I spacecraft, some 12 billion km (7.5 billion miles) from Earth, will introduce our civilization to interstellar space within the next 20 months as it reaches the termination shock of the solar system and passes into the heliopause. More astounding, Voyager continues to send weak telemetry that takes nearly twelve hours to reach its human creators on Earth.

While most space professionals and analysts advocate a balance of manned and unmanned space exploration, some in the space community are critical of human space flight activities. Their arguments are not widely held, but they are based on a pragmatic view of the situation. Human achievements in space (i.e., Apollo landings, International Space Station, etc.) are captivating, but some analysts argue that the scientific return from missions executed by unmanned vehicles is much more economical, safe, and effective.

It is not within the scope of this paper to justify robotic missions over their human-occupied counterparts; rather, the technology concept explored herein is one in which combined robotic/human exploration can flourish. Specifically, the advantages already realized in robotic space exploration could further enhance the design, operations, and utility of humans in space. To work through this exercise, this paper will investigate the design and operational considerations of an *aerial* robotic explorer on Titan, a moon of Saturn. Some of the mission characteristics exemplified by previous unmanned space vehicles will provide a good introduction to extra-planetary UAVs, and will be followed with further discussion based on the already successful human/robot interaction of terrestrial UAVs.

1.1 Unmanned Space Exploration

As alluded to previously, the benefit of robotics over a "man-in-the-can" approach to space exploration arises when the mission – whether in low Earth orbit or deep space – is to prepare, facilitate, or investigate sites which are of value for scientific or future human exploration purposes. It cannot, however, replace the on-site placement of the best computer in the world, the human brain. In point of fact, robotic missions do not yet offer the dexterity or intelligence of an astronaut. For all its success, the Mars Pathfinder rover *Sojourner* vehicle could only tediously explore a limited area around its landing site, and for all their potential, future spacecraft could not – at least in the near term – repair the near-sighted Hubble Space Telescope.

These examples highlight the basic yet powerful rationale for the deployment of robotic planetary explorers that can be controlled by humans in real-time. Therefore, in the context of this paper, "unmanned exploration" need not dictate great distances between the robotic explorer and the human controller. Indeed, this paper suggests that future astronauts have a cache of UAVs that can extend the reach and scientific return of a given mission. With such capability, future crews to Mars or Titan may never have to make the journey to the surface, but rather tele-operate air and ground vehicles from orbit without the cumbersome limitations of a long communications time delay.

As an introduction to the potential of robotic exploration, examples from the history of unmanned space flight will be presented which exemplify specific successes from previous (and on-going) missions. Of significant interest to both the space and UAV community should be the move toward the NASA-driven notion of "better, faster, cheaper" designs, and the lessons learned which have resulted from this paradigm shift.

Table 1: Select History of Unmanned Spaceflight

Notable System Quality	Mission/Date/Objective	Comments
Robust system design	Pioneer 10: 1972 – 1997+ Jupiter Exploration	- Continues contact with Earth 4 years, 1 billion miles after mission end - Did not speak (i.e., conserved power) until spoken to in 2001
Leveraging resources to satisfy multiple requirements	Voyager 2: 1977 – 1979+ Jupiter, Saturn, Uranus, Neptune Exploration	- Reduced onboard propellant by exploiting its targets' positions (i.e., unique planetary alignment) - Radio doubled as science and communications instrument
Out-of-the-box procurement/mission profile	Lunar Prospector: 1998-1999	- First competitively selected mission in NASA's Discovery Program - Mission concluded by impacting into lunar south pole to search for water
Cost-effective (not cheap) design	Pathfinder/Sojourner: 1997 Mars Exploration	- Proof of concept; done for the cost of a major Hollywood movie - Could Voyager have been done "better faster, cheaper?" Is another Voyager-class mission justifiable?
Innovative use of cutting edge technology	Cassini: 1997 - 2008 Saturn/Titan Exploration with Huygens atmospheric probe	- Solid state power supply/data recorder for long mission life - Radioisotope heater units to maintain storage temperature - Advanced structure and probe system

Unfortunately, the above list, while full of highlights, could be longer if not for several recent highly publicized failures. Like previous NASA failures, the losses of the Mars Polar Lander and the Mars Climate Orbiter reminded politicians and constituents alike what space engineers never forget: space exploration is unforgiving of mistakes. Recent scrutiny of certain errors within the unmanned space program has in fact raised questions about the "better, faster, cheaper" approach. Commenting on this criticism, former Jet Propulsion Laboratory Director Edward Stone explained

We were changing to a new era of missions, and we found the limit. We tried to do two missions for the price of Mars Pathfinder, and it was just too hard. We've learned a lot from this and have put in place new processes and a better safety net so that today's project teams won't face the same limitations as we had with Mars '98. We will continue doing missions more often in this new era, but do them in a robust way.[1]

Recent technical and programmatic failures open the door for the UAV community to extend both its applicability in space as well as its capabilities on Earth. Furthermore, the challenge for any future design within unmanned exploration – and particularly one as unique as a Titan Astroplane – is to walk the thin line that separates necessary cost-savings from unacceptable risk. One "lesson learned" from such a balance is that a design can quickly (and silently) reach a point where it contains greater risk liability than it offers in scientific (or monetary) dividends. While many other lessons can be derived from missions that have crossed the line, insight more applicable to an astroplane-type mission can be derived from the recently proposed "Mars Plane," a mission which never had to challenge the harsh environments of space.

1.2 Mars Plane

Before and after the Viking missions to the surface of Mars in the 1970's, several UAV exploration concepts have been studied, including Jason (JPL 1993), AEROLUS (Ames, Sandia 1993), and earlier ideas from Werner von Braun (1953) and NASA Dryden (1977). With renewed interest in Mars in the later 1990's, however, the Mars Plane received the most attention with respect to (if not progress towards) realizing the vision of planetary UAV advocates. Although the Mars Plane seemed to meet more public relations' requirements than scientific objectives, one can extract some important, yet limited insight from the proposed mission.

The Mars Plane, proposed in 1999, was intended to be a technology demonstrator for a concept that would facilitate planetary exploration, extraterrestrial logistics, and even potential site-to-site transportation for future Mars colonies. Although the mission of the Titan Astroplane will be decidedly different given lack of a "customer" on the surface, several common challenges can be taken from that study.

- **Technical:** Aerodynamics, flight dynamics, power/propulsion, and guidance/navigation all present significant challenges for robotic flight. The design requires transitioning a vehicle from hypersonic entry to stable, subsonic flight – all the while knowing where it is, where it is going, and what it is looking at. The operational environment of Mars (or Titan) compounds these technical difficulties by an order of magnitude over Earth.
- **Operational:** Human-machine interface, unfriendly environments, communications challenges, and even human error – which some argue are a result of the "better, faster, cheaper" approach – are a few of the potential "show stoppers" for a planetary UAV. Needless to say, flying a UAV in a dense,

[1] From "A Conversation with Dr. Ed Stone," http://solarsystem.nasa.gov/whatsnew/pr/010420B.html

methane-rich atmosphere with a pilot operating from orbit above gives a new meaning to “over-the-horizon, all-weather” ops.

With previous multi-million dollar missions becoming victims to operational curses, there exists opportunity for the space community and the UAV community to share knowledge from their defeats and victories. Before the technical solutions can be “down selected,” however, one must more thoroughly consider the operational aspect of the mission. This paper will employ a systems engineering approach to this problem, beginning with a discussion of the motivation for space exploration by UAVs and an evaluation of the design constraints UAVs will face.

2 Motivation

To date, unmanned air and space vehicles have been developed separately to accomplish goals of different mission types. The renewed interest in putting a UAV on Mars has initiated a discussion on how UAV technology might be used to accomplish space mission goals. This work is concerned with three main questions:

- What differences in aircraft technology might make UAVs better suited for scientific exploration on some other celestial bodies in our solar system?
- Within UAV system design, what sub-systems or design requirements are the most important in meeting space exploration mission needs?
- What technology developments are required, and how do these relate to and facilitate advancements in terrestrial UAV applications?

2.1 Space Exploration with Aerial Vehicles

Aerial systems exhibit operational behaviors and benefits that can potentially alleviate the deficiencies in current space exploration architectures. Whereas the duration of one-shot probes (Huygens, Galileo Probe) is measured in minutes and the range of a rover (Sojourner) is measured in meters – thus creating a limit as the volume and diversity of scientific data available – aircraft are highly mobile, can cover large areas, and can change flight plans more easily than a satellite. Given that the mission of most all robotic explorers is to collect and return data, it then follows that if bottlenecks in that data collection occur, they should be due to the sensor system, not the mobility of the vehicle platform. A UAV supports this idea.

Aircraft can also operate in the planetary environment with fewer limitations on access to interesting surface features. The ability to task the platform to move elsewhere, dynamically changing the mission plan, would also permit multiple locations – and atmospheric layers – to be searched, increasing the probability of finding conclusive scientific evidence of life or life supporting compounds. Additionally, the aircraft industry has developed years of experience in production line assembly and best practices which could be transitioned into developing a planetary UAV.

3 Unique Design Constraints

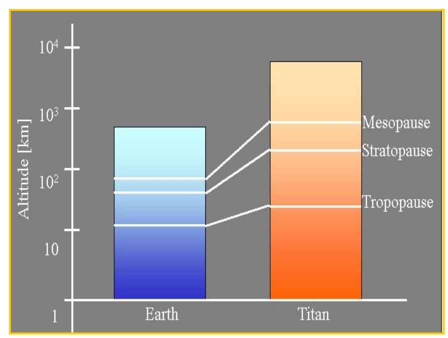
Given the evolution of vehicles within the UAV community, it is interesting to study the changes when the design is subject to a new set of constraints introduced by the environments of space and Titan itself. The following subsections describe attributes of space system design as well as the differences that might effect the technology development and operation of an interplanetary UAV.

3.1 Titan Environment

Arguably Saturn's most interesting moon, Titan is believed to represent Earth as it was 4 billion years ago, where processes believed to have formed complex organic molecules on Earth might still be ongoing. Titan has an atmosphere of nitrogen and methane, and is believed to have liquid water near its core. Titan has cloud formation over 1% of the surface, with methane rain contributing to its inhospitality. Scientists hypothesize the surface is rocky with lakes of methane and other organic compounds, offering scientific interest and engineering challenges for an interplanetary UAV. This environment, abundant in interesting scientific discoveries, contributes some unique engineering design conditions. The following table illustrates some important design variables from the environment of Titan.

Table 2: Titan Environmental Parameters

Distance from Sun	1.40×10^9 km
Distance from Saturn	1.22×10^6 km
Orbital Period around Saturn	16 Earth days
Diameter	5150 km
Gravity	1/7 Earth
Atmospheric Pressure	60% more than Earth
Highest Peak	2000 m
Cloud Coverage	1%
Cloud Ceiling	38 km
Primary Atmospheric Gases	Nitrogen, Methane
Surface Temperature	-178°C (-288°F)



Earth-Titan Atmosphere Comparison

Titan is interesting not only for its scientific value, but also for its technical challenges and potential mission resources. Operating in Titan's unique atmosphere, a Titan Astroplane might carry its oxidizer and use atmospheric methane for its fuel, much as airbreathing engines on Earth use an atmospheric oxygen oxidizer. This would substantially reduce the launch payload weight and allow a larger manifest of sensors on the vehicle. In this way, the Titan Astroplane could demonstrate the value of in-situ resource utilization (ISRU) as a key enabler to future space exploration.

3.2 Launch

The launch requirements often drive the design of a space system to the detriment of the scientific payloads. Because launch vehicles have prescribed dimensions into which a space vehicle must fit, the ideal spacecraft for launch is a cylinder, not a high aspect ratio wing. Modern satellites, requiring more power or more control than spin stabilization can provide, unfurl solar panels on orbit. A similar design constraint exists for the UAV wings; indeed, unless the vehicle is small enough to fit in the payload fairing, it must change shape from a stowed condition to its flight configuration.

Additionally, the launch environment is one of the most violent for structural system components. While the launch profile might be less than ten g's, the rocket shakes, often creating many tens of g's of force on components for short periods of time. Lightweight composite aircraft structures are effective in increasing flight performance, but designers will face a unique trade in developing materials for high performance flight that can survive the launch phase.

3.3 Deep Space Environment

Once beyond the protection of Earth's atmosphere and magnetic field, spacecraft are subject to conditions not typically found in normal UAV operation. Space is rife with micro-meteoroids that can penetrate and compromise aerodynamic surfaces, and protection – extra thick structural components or shielding material – is expensive in terms of launch weight and aerodynamic performance.

Solar radiation, which is so useful for generating power in space, contains ionized particles traveling at high speeds. Solar flares and other coronal mass ejections send large quantities of these ions into the solar system, colliding with all objects in their paths. Without the protection of Earth's magnetic field, electronic components on spacecraft must be carefully shielded to prevent degradation of electronic circuitry. Communication satellites have been lost when hit by solar flares, and given a transit time to Saturn measured in years and months, the probability of a Titan Astroplane encountering a similarly devastating ion environment is high.

3.4 Mission Duration

The vast distance between Earth and Titan require an extended spacecraft dormancy period. Aside from health and status monitoring updates and orbital correction maneuvers, the Titan Astroplane is unlikely to operate for durations on the order of years, depending on the orbital trajectory. Consequently, the system components must be designed such that they can be stowed and activated without any maintenance during the flight time.

3.5 Mission Concept

These following conceptual drawings reflect one potential scenario for UAV deployment form an orbiting mothership occupied by human controllers. A generic entry vehicle enters Titan's upper atmosphere . After slowed by drag, the payload is exposed and the balloon is deployed at subsonic speeds (Figure 1). Once stable balloon descent is achieved, the UAV is exposed, the systems are activated, and the vehicle is released. The vehicle then begins its survey mission of Titan. Note that the balloon is not discarded, but rather carries its own science and communications platform (Figure 2). Thus, the balloon platform helps extend mission duration, reliability, and capability. It also allows designers to offload systems from the vehicle to increase the payload mass.

Figure 1

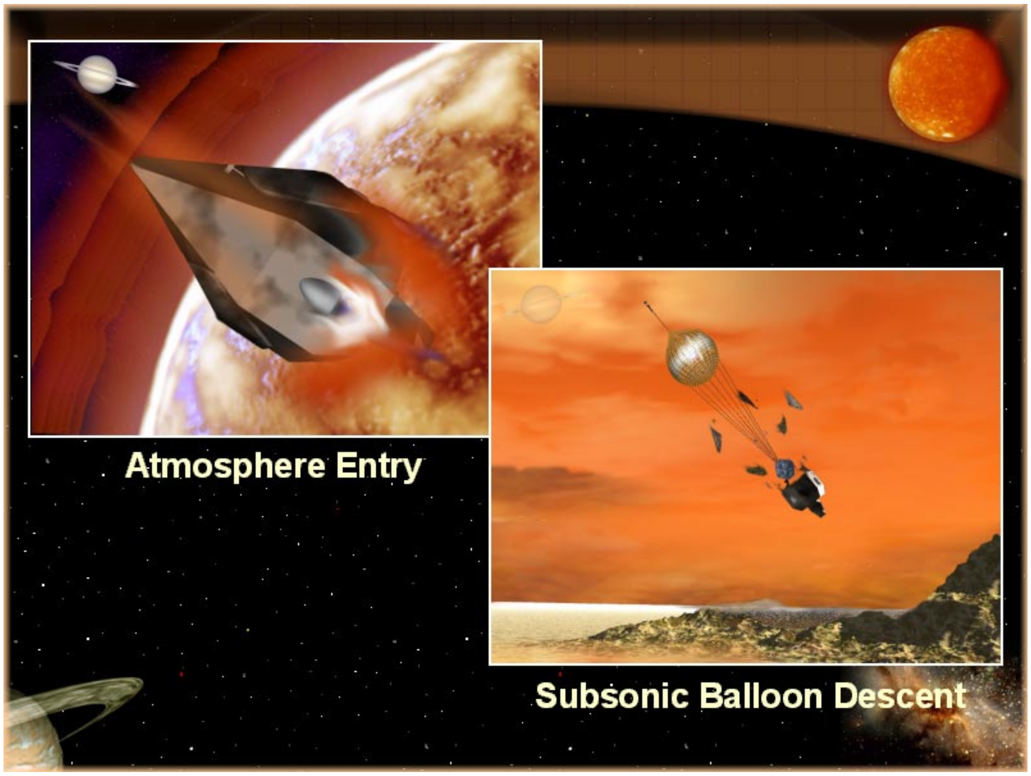
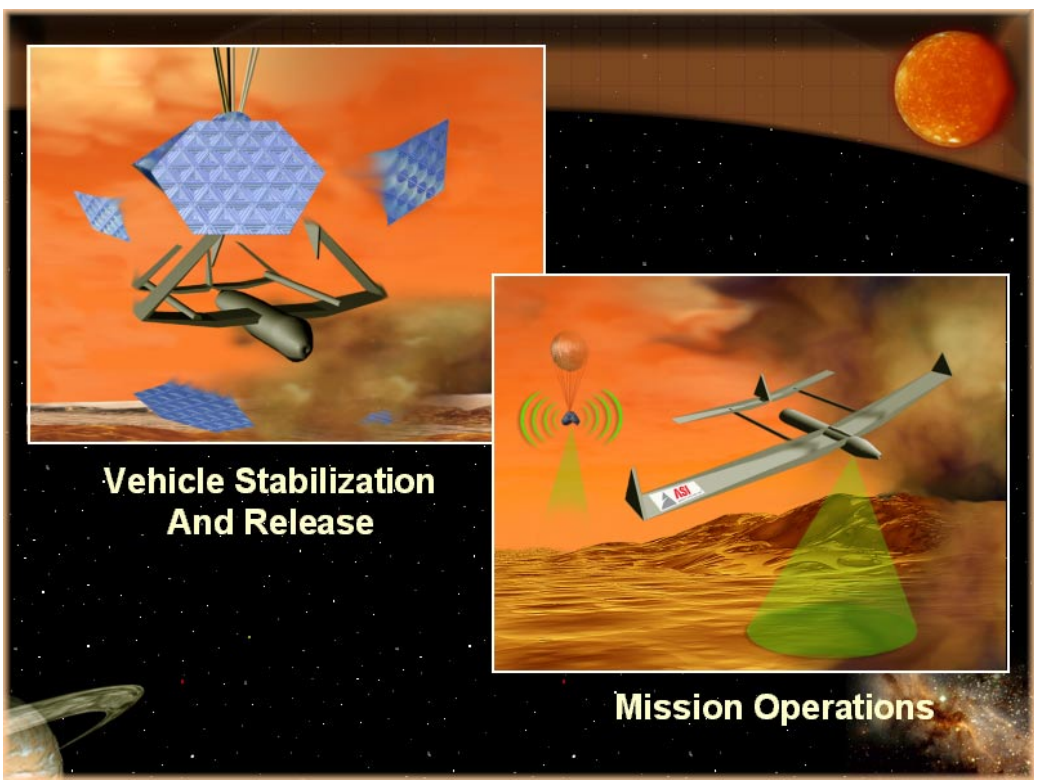


Figure 2



4 Analysis

For this work, aeronautic design requirements were analyzed for their ability to meet space mission needs and address constraints imposed by the space environment. Conclusions about the effectiveness of UAV design parameters and lessons learned from space technology and operational needs are presented.

4.1 Quality Function Deployment

One tenant of systems engineering work is based on functional and operational requirements of the system. If one cannot successfully identify the necessary design requirements and eliminate the superfluous "wants" of the design team, the final product could be over or under designed. To reduce this potential problem, Quality Function Deployment (QFD) is a useful tool that relates, ranks, and compares customer needs to traditional design requirements. The QFD diagram (Figure 3) was developed for the Titan Astroplane. As discussed below, several interesting insights can be drawn.

4.2 Preliminary Investigation and Results

Many design requirements, in addition to their satisfaction of customer needs, raise some interesting points of discussion with respect to the use of UAVs in planetary exploration. Some of the salient issues surrounding the requirements and their QFD ranks are highlighted below.

Guidance, Navigation, and Control (1)

- As with most mobile systems, GNC was deemed to be the most important of design requirements. It scored high in the QFD analysis due to the fact that it enables accurate human control, reliability, platform stability, and ensures a high return on data quantity and quality. In addition, a GNC system would facilitate multiple exploration scenarios (i.e., more bang for your buck). This was made possible through a strong relationship with "Adaptable UAV operations and hardware" and a weaker correlation with the "Maximize Payload" customer need.
- Vehicle GNC did not create any negative correlations.
- The Global Hawk is an example of effective use of a UAV-based GNC system, offering a multi-role capability to provide intelligence, surveillance, and reconnaissance as well as serve as an advanced communications node.

Figure 3: QFD Diagram

CATEGORY	RELATIVE RANK W/IN CATEGORY	LEGEND: -- 9=Strong Correlation 3=Moderate Correlation 1=Weak Correlation -1=Negative Correlation	Auto Control & Mission Planning	Independent Deployment and Cruise	GNC	Dynamic Retasking	Error Detection and Correction	Redundant Components	Special Grade Parts with high MTBF	No common failure mode	Engine off Glide	Data Relay	High Endurance	Long Range	Multiple Sensor	Plug-and-Play Sensors	Advanced, LW Structure	Minimize System Components	High Efficieny Propulsion	High Efficiency Power	Safe Modes	Diagnostic and Health Monitoring	Large Coverage Area	High Data Rate/High Band Width	Bit Error Rate	Aerodynamic Efficiency	Use of COTS	Conventional Materials	Small-scale Systems	Propulsion ISRU	Off-board Systems	Multiple Vehicles	No Solar Power Generation	Hardened Components	Power Generator	Power Storage	Furled Compnents	Effective Deployment
		Requirement Rank:	8	20	1	5	16	18	28	5	27	15	25	25	12	2	34	11	20	23	35	16	36	5	33	8	23	29	29	3	10	3	13	32	20	13	29	19
CAPABILITY	1	Autonomous	9	9	3	3	3			3											-1	3										3			9			3
	1	Reliable		1	9		9	9	9	9	9	1			1	1		3	1	1	3	3			3	3	1		1	-1		3	3	3	3	9		3
	1	Available					3	3		9	1							3				3					1			-1		3	3	3	3	3	-1	3
	1	Multiple Scenarios	9		9	9							9	9	9	9		-1	1	1				3		3			1		1	9				1		
	1	Maximize Payload			1			-1				9	-1	-1	1		9	3	9	9						9			-1	9	9	1		-1	-1	-1	1	3
	1	No Maintenance						9	9	3		1			-1			9	9	9	-1	3					1	3				1	1	1	-1	1	-1	1
	1	Data Quantity	3		1						3	9	9	9	9	3		-1	1	1				9								9						
	1	Data Quality	9		3	9	9								9							3		9	3						1	-1						
	1	Stable Platform	1	3	9	3					3						1		1		1	3				9			-1		1						-1	9
EFFICIENCY	1	Adaptable Ops/HW	3		9	9					3		3	3	3	9		-1	1	1				3			1		-1	3	3	3			3	9		
	1	Ease of Production	-1	-1					-1			-1			-1	9	-1	3									9	9	-1	-1	9		3	-1	-1	1	-1	-1
	1	Leverage Resources																								3				9	3		-1		3	-1		
	1	Economies of Scale														9		1									3	3	9		1	9						
CONSTRAINTS	1	Atmosphere Conditions	3	3		3				3									1					3	3	9			-1	9	1		9		3	3		1
	1	Solar Radiation								3																							-1	3				
	1	Space Environment					3	3		3																							9	3		3		
	1	Launch Vehicle Integration		9												1		3								-1	3		9	3		-1	3				9	3
	1	Long Travel/Storage Time	-1					3		3								9				9								9				3	3	1	9	
	1	DSN Compatible										9												9	3		3				3							
		Totals:	35	24	44	36	27	26	17	36	19	28	20	20	30	41	9	31	24	22	2	27	0	36	12	35	22	15	15	39	32	39	29	14	24	29	15	25
			Auto Control & Mission Planning	Independent Deployment and Cruise	GNC	Dynamic Retasking	Error Detection and Correction	Redundant Components	Special Grade Parts with high MTBF	No common failure mode	Engine off Glide	Data Relay	High Endurance	Long Range	Multiple Sensor	Plug-and-Play Sensors	Advanced, LW Structure	Minimize System Components	High Efficieny Propulsion	High Efficiency Power	Safe Modes	Diagnostic and Health Monitoring	Large Coverage Area	High Data Rate/High Band Width	Bit Error Rate	Aerodynamic Efficiency	Use of COTS	Conventional Materials	Small-scale Systems	Propulsion ISRU	Off-board Systems	Multiple Vehicles	No Solar Power Generation	Hardened Components	Power Generator	Power Storage	Furled Compnents	Effective Deployment

Plug and Play Sensors/Components (2)

- The concept of developing components and sensors that can be interchanged allows a single production vehicle concept to accomplish multiple missions. A "Plug and Play" Design requirement directly addresses the performance needs of a multi-mission role and enhances the production efficiency through adaptable hardware and benefits from mass production and economies of scale. There is weaker correlation with Reliability and Launch Vehicle Integration, as this concept allows for the replacing of components much easier.
- Plug and Play Components did not result in any negative correlations.
- Many existing reconnaissance aircraft use swappable payload components to accomplish multiple missions without exceeding payload limits on any one vehicle. Electronics and Robotics systems are moving to modular components that can be mass-produced and integrated for specific mission tasks. Such techniques have been limited in space engineering due to the lack of access to on-orbit repairs. The Hubble Space Telescope has received upgrades to modular systems to extend the spacecraft life.

Multiple Vehicles (3)

- The delivery of an armada of UAVs into the atmosphere of Titan provides the obvious benefit of multiple scenarios and high data quantity for a given mission. In addition, the "Multiple Vehicles" requirement enhances mission autonomy, reliability, availability, and mission adaptability. In terms of mission cost-effectiveness, multiple vehicles provide the opportunity to achieve "Economies of Scale" within the program, with perhaps even an assembly line development process for tens or hundreds of UAVs.
- Negative traits introduced by multiple vehicles include obvious launch vehicle integration problems as well as potentially reduced data quality given that smaller sensor payload of an individual vehicle. This problem, however, could be addressed through the use of cooperative robotics.
- There are currently no known examples of UAVs employing a "swarm" approach to mission operations. A military example would include MRVs (multiple reentry vehicles) on nuclear warheads, which reenter the atmosphere under a single aeroshell before dispersing to increase reach and effectiveness.

Propulsion ISRU (3)

- Propulsion ISRU ranked high for its ability to reduce consumables mass (and thus increase the available payload mass), leverage the available resources on Titan, and mitigate the atmospheric constraints that a standard propulsion system would face on Titan. By using the readily available methane fuel at Titan, the constraints posed by the "Long Travel/Storage Time" and "Launch Vehicle Integration" were reduced due to less of a need for heavy cryogenic storage hardware for the methane en-route.
- Disadvantages of Propulsion ISRU include the introduction of reliability and availability problems during the in-situ portion of the mission and design features, which introduce complexity and counter the need for "Ease of Production."

- While the most common example of propulsion ISRU are Earth-based airbreathing engines, extraterrestrial ISRU has yet to occur. NASA is currently developing Mars ground-based ISRU systems for launch later this decade.

Dynamic Retasking (5)

- Dynamic Retasking primarily addresses the needs to accomplish multiple mission scenarios, adapt to changing mission conditions, and return high quality data. There is medium correlation with the ability to be autonomous (if necessary) and stable while operating in an alien atmosphere.
- There are no negative correlations.
- Military UAVs constantly receive new orders once on station. If a particular location does not contain the desired intelligence, the aircraft can move elsewhere to continue looking. Similarly, Voyager II was able to alter course at Saturn and continue to explore the outer planets Uranus and Neptune.

Aerodynamic Efficiency (8)

- Optimizing the aerodynamic efficiency of the vehicle will increase the stability and payload capacity of the UAV. To a lesser extent, the aerodynamics will increase the reliability, enable multiple scenarios (through increased range and reduced fuel consumption), and leverage the available atmospheric resources/conditions on Titan.
- No major negative correlations were found for the "Aerodynamic Efficiency" design requirement. If a high aspect ratio wing is required, a conflict with launch integration may arise.
- Any long range or extended duration aircraft must be aerodynamically efficient. In the UAV community, this is perhaps best exemplified by the Global Hawk aircraft, which offers a flight duration of 36 hours.

Off-Board Systems (10)

- Mission needs of maximizing the payload and efficiently producing the vehicle can me met by moving some systems off the UAV, making room for additional sensors and reducing the system complexity of the vehicle itself. There is moderate correlation with adaptable hardware and the ability to leverage other resources, such as the orbital transfer vehicle. Due to the potential of using a communication relay with Earth should local pilot communications be lost, the system must interact with the Deep Space Network. There exists a weak correlation with multiple scenarios, data quality, platform stability, economies of scale, and atmospheric conditions.
- There are no negative correlations.
- The Mars Pathfinder mission used the landing vehicle as a communication and data relay between the rover and Earth. Bistatic radar separates the receiver from the source moving the signal collection systems off the signal generation platform.

In addition to the most valuable design requirements which should be incorporated, insight can also be gained from examining the lowest ranked design qualities as determined by the QFD analysis. Specifically, one can see how commonly used “solutions” in planetary exploration do not apply to a Titan Astroplane, yet how those technology and operation requirements – although rare in the UAV community – may enhance UAV development on Earth.

Engine Off Glide (27)

A requirement to continue operation after an engine failure correlates with a need for reliability. However, because an interplanetary vehicle is not typically recovered and the overall flight time is relatively small, the ability to maintain stability after an engine failure is not as important as other design considerations.

Advanced Light Weight Structures (34)

Advanced lightweight structures are the future of terrestrial aircraft systems. Due to the constraints of launch and the space environment, lightweight structures trade payload space for reliability and should not dictate the design.

Safe Modes (35)

Safe modes are used extensively on space systems to isolate sub-system failures and save the spacecraft; however, the correlation with space mission needs for a Titan UAV was low. However, safe modes, while not as important for design consideration on Titan, may be valuable to Earth-based UAVs that fly over populated areas.

5 Conclusions

Many of the design requirements traditionally addressing terrestrial UAV technology and operations can facilitate the goals of space exploration missions. A “pilot-in-orbit, vehicle in atmosphere” architecture encourages semi-autonomous designs with GNC, Mission Planning, and Retasking functions that could significantly advance “Over-The-Horizon” UAV operations. In point of fact, advanced decision-making capabilities currently in testing on space platforms would allow for beyond line of sight, *yet real time* operations for astronauts orbiting another planetary body. Thus for relatively simple vehicle designs, such tools would decrease mission risk while increasing data return. In addition, by reducing the need for astronaut surface operations, such “exploration from orbit” would help meet the robust and cost-effective criteria of NASA.

In conclusion, space and UAV mission needs, while distinct, have interesting overlaps where aircraft technology and practices might better address space exploration requirements. To promote this goal, it is necessary to understand the customer needs and requirements of space missions and the role UAVs can play in space. Such work requires knowledge of the current and future path of terrestrial UAVs coupled with a fundamental understanding of NASA’s Space Science and Human Exploration and Development of Space Enterprises. Once this is done, future technology roadmaps for synergistic human-robotic space exploration will be able to leverage technology concepts, operations, and best practices of both the space and UAV communities.